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МІКРОХВИЛЬОВА РАДІОМЕТРІЯ В МЕДИКО-БІОЛОГІЧНИХ ЗАСТОСУВАННЯХ

Резюме. *Радіометрія в медико-біологічних проблемах пов'язана з необхідністю вимірювання слабких сигналів та використанням апаратури з флуктуаційною чутливістю (10^{-15}–10^{-17}) Вт, що є складною технічною задачею, особливо в діапазоні (37–78) ГГц (міліметрових хвиль), вирішення якої можливе на базі нових варіантів високочутливої радіометричної апаратури. Наведено результати дослідження та реалізації схем модуляційного радіометра з використанням структурно-алгоритмічного методу, в якому досягається протифазне придушення рівня власних шумів та підвищення на порядок чутливості у порівнянні з відомою схемою, а також метод поглиблення модуляції сигналу за рахунок введення позитивного зворотного зв'язку, який забезпечує підвищення чутливості у понад 10 разів. Отримано нові можливості для дослідження електромагнітних полів і випромінювань (ЕМВ) біологічних об'єктів та об'єктивізації можливого інформаційного електромагнітного обміну на різних частотах як у тілі людини, так і тіла з навколишнім середовищем. Вирішено також проблеми метрологічної підтримки лікувальної апаратури низькоінтенсивних сигналів для технологій квантової медицини – мікрохвильової резонансної терапії, міліметрової й інформаційно-хвильової терапії, що використовують монохроматичні та шумові сигнали, інтегральна потужність яких може перебувати в межах (10^{-6}–10^{-12}) Вт. Запропоновані технічні рішення поряд із забезпеченням необхідної чутливості розширюють функціональні можливості радіометричної апаратури стосовно дослідження об'єктів живої природи та організму людини.*

Ключові слова: *радіометрія, інтегральна потужність, електромагнітне випромінювання, біологічний об'єкт.*

A. Yanenko

MICROWAVE RADIOMETRY IN MEDICO-BIOLOGICAL APPLICATIONS

Summary. *Using of radiometry in medical and biological problems is associated with the need to measure weak signals and apply equipment of fluctuating sensitivity (10^{-15}–10^{-17}) W. This is very complex engineering task, especially in the range of (37–78) GHz (mm- waves), and its solution must be based on new variants of highly sensitive radiometric equipment. In the paper structural variant of modulation schemes radiometer has been presented using structural and algorithmic method, in which antiphase suppress of the intrinsic noise level is achieves and increase of the sensitivity, compared with the known pattern, as well as the method of deepening modulation by introducing positive Feedback communication, which enhances the sensitivity more than 10 times. As a result, a number of new possibilities for the study of electromagnetic fields and radiation (EMR) and the objectification of possible biological objects electromagnetic information exchange at different frequencies, both in the human body and with the environment, were obtained. Problems of metrology control of low intensive signals of medical equipment for Technologies of Quantum medicine – microwave resonance therapy, millimeter and informational wave therapy that use monochromic and noise signals the integral power of which is within (10^{-6}–10^{-12}) W. Engineering solutions along with providing of the necessary sensitivity extend the functionality of radiometric equipment dealing with the study of objects of nature and the human body.*

Key words: *radiometry, integral power, electromagnetic radiation, biologic object.*

Introduction. The development of microwave electronics and its elemental base in the last 25–30 years stimulated the creation of new radiotechnical means in the field of microwave measurements of weak signals, including their radiometric methods and structures. This fact, in turn, contributed to the increased use of radiometric equipment in various fields of science and technology – traditional radar and navigation, astronomy and meteorology, and a comparatively new biophysics, biology and medicine [1–4].

The dissemination of new technologies of treatment which are using low-intensity microwave signals, such as microwave resonance therapy (MRT), information-wave therapy, millimeter therapy, which are combined with the common name «quantum medicine» [5,6]. The term «quantum medicine» describes low intensity of signals are used (at the level of energy of the quanta). These technologies use the frequencies of (37–78) GHz (i.e., mm-band) and low-level affecting signals, (10^{-2}–10^{-12}) W/cm^2. Such low signal levels can be measured by highly specialized receivers, e.g. П15 (P15), or by non-standard radiometric apparatus which is certified in prescribed manner [6].

The last one is promise to be useful for early diagnosis of diseases that are associated with the presence of thermal irregularities in humans, as well as for the study of EMR of the biological objects and of the human body characterizing the exchange of information both within the living organism and with the external environment.

Thus, development and deepening of biomedical researches and technologies require creation of the highly sensitive radiometric equipment by using new achievements of microwave technologies and the element base and exploring possible directions for their use.

The problem that must be solved in radiometric instrumentation of the quantum medicine technologies is a metrological support.

Ultra-low levels of monochromatic or noise EMR are used in the new microwave technologies. The minimum value of integral power of monochromatic EMR (e.g., ARIA-SC, AMPT-02) can be (10^{-10}–10^{-12}) W, and the power spectral density of the noise signal is (10^{-16}–10^{-21}) W/Hz (Порог-3, Порог ВТ, Порог НТ, Коверт-01 (Threshold-3, Porog VT, Porog NT, Covert-01). For such power levels of measuring it is necessary for settings of the radiometric sensitivity to be higher at least on the order from the power magnitude, and the measurement accuracy to be not worse than in the equipment for the standard range of power, i.e. (10–15)% [6].

Early diagnosis and measurement of thermal irregularities within the human body (at the (50–80) mm of depth) is possible with the radiometer operating at low frequencies, (0,9–1,5) GHz, and the sensitivity of such equipment should be at the level of (10^{-15}–10^{-16}) W.

The research of natural electromagnetic fields and radiation and their interaction with the environment also requires the development of radiometric equipment with the sensitivity of the order of (10^{-14}–10^{-16}) W, depending on the range of operating frequencies.

Classification of medical and biological problems that can be solved with the use of microwave radiometry equipment was developed (fig.1).

Analysis of the fig.1 data shows that, depending on the task of the biomedical applications, operating frequency range of radiometric equipment can vary from a few to hundreds of gigahertz, and the sensitivity – from 10^{-13} to 10^{-17} watts.

Implementation of structural schemes of radiometric equipment of such sensitivity is usually performed using the compensation, correlation or modulation method of transformation of input signals [7].

Of these methods the most widely are used modulation methods that provide sufficiently high sensitivity and accuracy of measurement, as well as having a simple and reliable implementation of the scheme. In turn, a block diagram of a modulation of the radiometer can be performed by direct conversion of the input signal when the basic amplification is reached at the frequency of the input signal and the superheterodyne conversion, in which the main gain is attained at the intermediate frequency.

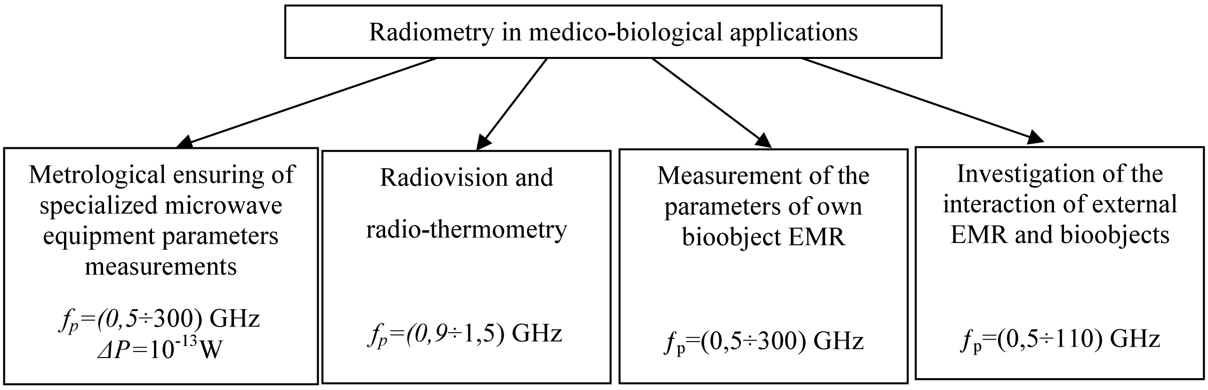

Figure 1. Classification of radiometric problems in the medical and biological applications

Рисунок 1. Класифікація задач радіометрії в медичних та біологічних застосуваннях

Fig.2 shows a block diagram of a radiometric system (RMS) with heterodyne conversion of input frequency.

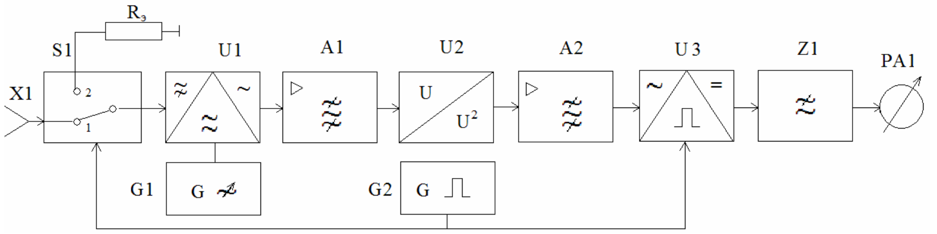

Figure 2. Block diagram of the modulation RMS (X1-input antenna, Re – dummy, S1 – modulator, U1 – mixer, G1 – heterodyne, A1 – intermediate frequency amplifier, U2 – quadratic detector, A2 – switching frequency selective amplifier, U3 – synchronous detector, Z1 – low-pass filter, PA1 – indicator, G2 – modulating frequency generator)

Рисунок 2. Блок-схема модуляційної РМС (X1 – вхідна антена, Re – еквівалент антени, S1 – модулятор, U1 – змішувач, G1 – гетеродин, A1 – підсилювач проміжної частоти, U2 – квадратичний детектор, A2 – селективний підсилювач, U3 – синхронний детектор, Z1 – фільтр нижніх частот, PA1 – індикатор, G2 – генератор модуляційної частоти)

On the square-law detector, output for the period of commutation switching signal is generated [7]

$$U_k(t)=\alpha_k\frac{U_1-U_2}{2}\,sign\sin\Omega t+2U_w^2(t)\sum_{i=1}^{n}\left[[(\Omega\pm\Omega_i)t+\varphi_i]\right], \qquad (1)$$

where α_k – transfer coefficient of RMS channel to a quadratic detector include, U_1–U_2 = ΔU^2 – voltage difference for the switching period, which characterizes the input signal power, $sign\sin\Omega t$ – switching function, $2U_w^2(t)\sum_{i=1}^{n}[(\Omega\pm\Omega_i)t+\varphi_i]$ – the total voltage of the thermodynamic noise component of the radiometric channel (RMC) from the front antenna to the square-law detector.

Voltage (1) through a selective amplifier A2 enters the synchronous detector U3 and after appropriate conversion by low pass filter Z1 allocated output voltage modulation of the RMS

$$U_{pc} = \alpha_{pc} \frac{2}{\pi} \left[\frac{\Delta U^2}{\pi} + 2U_w^2(t) \sum_{i=1}^{n} [\,(\Omega - \Omega_i)\, t + \varphi_i\,] \right], \tag{2}$$

where α_{pc} – total conversion coefficient of the RMS channel.

The first term of equation (2) is a DC voltage; it is proportional to the power of the measured input signal (ΔU^2), and the second - alternating voltage noise passing through the filter systems of the RMS conversion channel. Spurious noise components presented in equation (2) cause a slow indicator pointer fluctuation and reduce the sensitivity of MRS.

Therefore, sensitization is an urgent task for the RMS used in health and biological applications and is achieved in several ways.

Firstly, the decrease in the level of thermodynamic fluctuations can be achieved by optimal design and technological solutions (shielding, use of low-noise components and assemblies, etc.), and secondly by increasing the number of samples and the measurement time, which naturally reduces the speed of RMS.

Reduced fluctuations in the thermodynamic power can be calculated with the formula [8]

$$P_w = 4\, k\, T\, \Delta f \,/\, n, \tag{3}$$

where n – number of samples, k – Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K), T – is the temperature of the environment, Δf – bandwidth of the RMS channel to square-law detector.

The number of samples for the measurement time t_0 can be written as

$$n = t_0 \,/\, t_F, \tag{4}$$

where t_F – period of the selected frequency of output noise spectrum**.**

With regard to (4), equation (3) takes the form

$$P_w = 4\, k\, T\, \Delta f\, t_F \,/\, t_0. \tag{5}$$

Using equation (5) we can calculate the power of thermodynamic fluctuations for different frequencies of the noise spectrum and thus identify opportunities of MRS in sensitivity, speed, and use for solving biomedical problems – metrological assurance, thermometry and research purposes.

For example, in the modulation RMS at switching frequency of 1 kHz for one sec over 10^3 samples are averaged. Radiometric channel bandwidth is usually selected in the range of 10^6 to 10^8 Hz, thermodynamic power fluctuations at ambient temperature T = 293 K will be $P_w = 1.6\ (10^{-17}–10^{-15})$ W, which is sufficient for use of such RMS in biology and medicine.

Power reduction of the thermodynamic fluctuations may be achieved also by decreasing the bandwidth of frequency selective filter switching amplifier A2 by selecting it in the range (10–100) Hz. At the same time, as shown by experimental studies [9], with a narrow band ($\Delta F \leq 20$ Hz) great influence on the sensitivity has temperature, under the influence of which the filter parameters and the oscillator frequency switching change.

Promising to increase the sensitivity of the modulation radiometer is the use of structurally algorithmic method developed by the authors [10]. A distinctive feature of the radiometer block diagram that implements this method is the introduction of a negative voltage feedback in frequency of noise spectrum that provides their additional suppression. fig.3 shows part of the scheme, which provides selection of the noise components and implements methods to suppress them. The scheme is connected between the output of the quadratic detector U2 and input switching frequency selective amplifier A2 (fig.3).

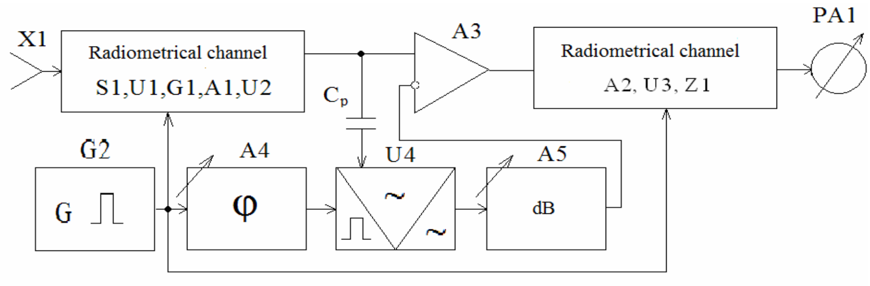

Figure 3. Noise reduction scheme of the modulation radiometer (A3 – operational amplifier, A4 – phase shifter, U4 – multiplier, A5 – attenuator, C_p – capacitor)

Рисунок 3. Схема зниження шуму модуляційного радіометра (А3 – операційний підсилювач, А4 – фазоповертач, U4 – помножувач, А5 – атенюатор, C_p – конденсатор)

The method is as follows. Voltage (1) is fed to one of inputs of operational amplifier A3. Variable noise component via the capacitor Cp is fed also at one of the inputs to the multiplier U4, the second input via the phase shifter A4 receives the voltage from the oscillator of the switching frequency G2.

Because of multiplying of voltage at the output U4 the switching frequency get twice, which further is delayed by selective filter, and voltage noise components

$$U_{pc}(t) = \alpha_{pc}\frac{\Delta U^2}{2}\, sign\sin 2\Omega t + 2U_w^2(t)\sum_{i=1}^{n}\left[[(\Omega \pm \Omega_i)\,t + \varphi_i]\right]. \tag{6}$$

Voltage (6) is fed to the second input of the operational amplifier A3, at the outputs a difference between the two voltages (1) and (6) is received.

Appropriate choice of the phase relations of the phase shifter A4 and amplitude shifter - attenuator A5 provides minimum indicator readings at the closed reception antenna X1, which is the maximum suppression of noise components and thus the sensitivity of RMS increases. According to the source data [10], considered scheme provides increased sensitivity of up to 10 times.

The method of automatic modulation deepening by introducing the positive feedback can also serve as possible way of increasing the sensitivity of the modulation scheme RMS [11].

This is achieved by further including of adder A1 at the input of the standard radiometric channel, noise generator G1, attenuator A2 and positive feedback loop voltage divider A3 (R1, R2) (fig.4). At the first input of adder A1 the receiving antenna X1 is connected and at the second input noise generator is connected via attenuator A2. Output of the RMS via a voltage divider A3 is connected to the control input of the attenuator A2.

The constant component of the output voltage of the MRS (1) is applied to the attenuator A2, transfer coefficient of which is set proportional to the magnitude of the voltage

$$K_{A1} = U_{pc}\,\beta, \tag{7}$$

where β – transfer coefficient of the divider A3.

The given schema changes of the constant voltage component (1) can be written as follows:

$$U_{pc} = \alpha_{pc}\frac{2}{\pi}\left(\frac{\Delta U^2}{\pi} + K_{A1}\,\bar{U}_{A1}^{2}\right), \tag{8}$$

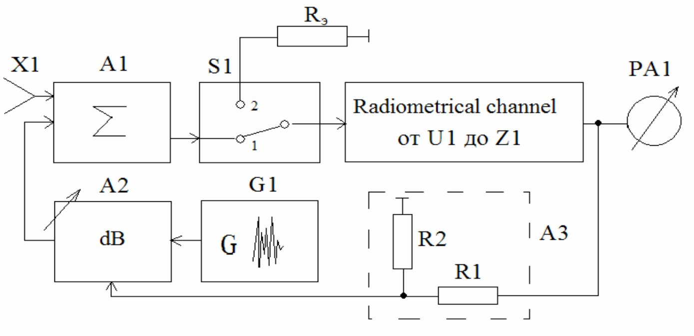

Figure 4. Diagram of the MRS sensitivity increasing due to the introduction of the positive feedback (A1 – adder, A2 – attenuator, A3 – resistive divider R1\R2, G1 – noise generator)

Рисунок 4. Схема підвищення чутливості РМС завдяки застосуванню додатного зворотного зв′язку (A1 – суматор, A2 – атенюатор, A3 – резистивний дільник R1\R2, G1 – генератор шуму)

Substituting the values of (7) in equation (8) and performing transformations relatively to the output voltage we obtain

$$U_{pc} = \frac{\alpha_{pc}}{1-\alpha_{pc}\beta\bar{U}_{A1}^{2}}\Delta U^2. \tag{9}$$

In the absence of an additional signal from the generator G1 (β =0) the output voltage of the MRS has the form

$$U_{pc}^{/} = \alpha_{pc}\,\Delta U^2.$$

When the signal input ($\beta > 0$), attenuator A2 is opened and the signal from the noise generator G1 extends to the adder, resulting in an increase in the modulation depth (the switch S1 is in position «1»), and this is equivalent to increase of the RMS sensitivity in time

$$\frac{U_{pc}}{U_{pc}^{/}} = \frac{1}{1-\alpha_{pc}\beta\bar{U}_{A1}^{2}}\quad, \tag{10}$$

where $\bar{U}_{A1}^{2}$ – the dispersion of the noise signal generator G1.

Increasing of the sensitivity of such scheme for the data source [11] may be more than 10 times and is limited to the values at which the circuit excitation occurs.

Promising direction to use the microwave radiometric equipment is studying the parameters of own electromagnetic radiation (EMR) of living organisms.

Fig.5 shows the classification of the possible parameters of bioobject own EMR, measurement of which can be performed using radiometric equipment.

The above embodiments of circuits can be used to measure the power of electromagnetic radiation of the whole organism, to the determining the temperature anomalies and their location. To study the structure of the microwave EMR, for example, for the allocating a bioinformatics component the MRS schemes listed in [12,13] can be used. A distinctive feature of the automatic RMS [13], is the using of the differential method of measurement in combination with two antennas-sensors, which provide a bioinformatics component selection.

Output voltage of the bioinformatics components in the automatic MRS can be written as

$$U_{pc} = \alpha_{pc} (I_1 - I_2), \tag{11}$$

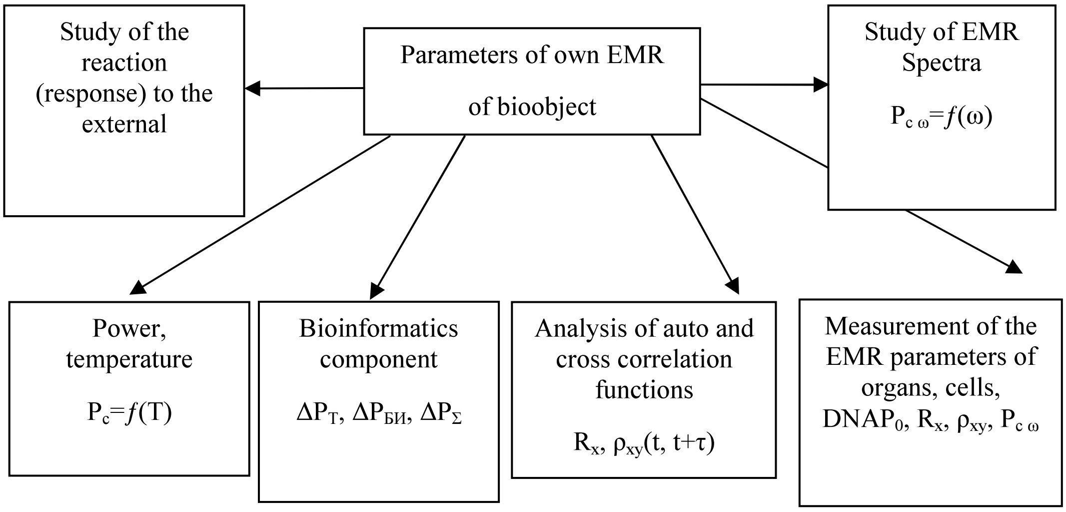

Figure 5. Classification of measuring tasks in the study of the bioobject own EMR

Рисунок 5. Класифікація задач вимірювання при вивченні власного електромагнітного випромінювання (ЕМВ) біооб'єкту

Output voltage of the bioinformatics components in the automatic MRS can be written as

$$U_{pc} = \alpha_{pc} (I_1 - I_2), \tag{11}$$

where I_1 – total intensity of the EMR, I_2 – intensity of thermal radiation, α_{pc} – total coefficient of the RMS measuring channel conversion.

For reliable signal recording the sensitivity of such circuits, operating on the difference signals, should be at the level (10^{-15}–10^{-16}) W.

Another area to use radiometric equipment when examining biological objects own EMR is to measure the correlation characteristics of the radiation. Thermal radiation, which is formed in equilibrium processes, has a noise character, and its intensity is proportional to the temperature of the object T. Bioinformational (non-thermal) radiation at the cellular level, which is determined by non-equilibrium processes and provides synchronization of the body, is determined. Because of the small size of the cells, EMR energy density reduces in many times in a short distance from the bioobject, moreover, it is accompanied by a stochastization of the radiation. The total radiation of a living organism can be represented as a superposition of deterministic and noise signal

$$U_\Sigma (t) = U_\omega (t) + U_T (t). \tag{12}$$

Register weak deterministic signal $U_\omega (t)$ against the background of strong noise signal $U_T (t)$ is a difficult technical task, which is only possible with the use of specialized high-sensitivity RMS that measures the autocorrelation function.

Radiometric system [14], while measuring the power density bioobject EMR allows you to register the autocorrelation function of the signal. Output voltage of the MRS in this case has the form

$$U_{pc} = \frac{\alpha_{pc}\left[1 - R_x(\tau)\right]}{R_x(\tau = 0)} \Delta U^2, \tag{13}$$

where $R_x(\tau)$ – normalized correlation function of the antenna signal for various values of delay τ.

Register autocorrelation function opens the possibility of identifying deterministic processes that can be masked by noise and thus to identify the source of bioinformatic radiation of the living organism.

An important parameter may be the cross-correlation characteristics of the two signals, providing registration of distribution (location) of the deterministic signal on those or other bioobject areas.

A two-input single-channel differential correlational of the RMS, given in [15], allows such measurements. The output voltage of the RMS contains information on the correlation coefficient

$$U_{PC} = \alpha_{PC}\, \rho\, \bar{U}_1^2\, \bar{U}_2^2, \tag{14}$$

where ρ – cross-correlation coefficient of the bioinformatics signals, $\bar{U}_1^2, \bar{U}_2^2$ – dispersion of uncorrelated radio thermal signals of the input antennas of the RMS.

Measurement of inter-correlation function allows exploring the gradients of temperature fields in the presence of selected sources in the bioobject body (local thermal irregularities). Sensitivity of such RMS must be on the level of (10^{-16}–10^{-17}) W.

Temperature anomalies in alive organism arising from tumors, trauma, inflammation, etc. strongly influenced the frequency features of EMR. Localization of the thermal irregularities sources may be at different depths from the body surface. Emission wavelength varies depending on the depth of its occurrence. Therefore, recording the frequency dependences of the intensity of EMR can detect and localize thermal irregularities sources in the human body.

Block diagram of such a spectrum analyzer shown in [16] allows to perform such measurements. At the output of the RMS at the automatic tuning of the heterodyne frequency constant voltage of the following form is recorded

$$U_{PC} = \alpha_{PC} \frac{\Delta \bar{U}_i^2(\omega_i)}{\bar{U}_0^2(\omega_0)} U_=, \tag{15}$$

where $\Delta \bar{U}_i^2(\omega_i)$ – change in the variance of the signal at analysis frequency with respect to the initial frequency, $\bar{U}_0^2(\omega_0)$ – dispersion of the signal at the initial frequency, $U_=$ – DC voltage of the reference source.

Shape of the curve in the coordinates of frequency-voltage $U = f(\omega)$ provides information on the nature of the thermal irregularities and temperature gradient inside the object. Intensity on the frequency coordinate allow determining the depth of the source of thermal radiation.

Conclusions. Alive organisms are characterized by large set of parameters of their own microwave EMR; its measurement and study contributes not only to deepen the knowledge of living objects, but also in the development of new diagnostic and treatment methods.

The radiometric methods and tools have great potential for solving of practical and research problems in biology and medicine – of metrological provision of specialized equipment, diagnosis of the state of alive organism, the study of the own microwave EMR parameters and their links with environment.

Radiometry is used in the biomedical applications due to the need for sensitivity to fluctuation to the level (10^{-15}–10^{-17}) W, which is a complicated technical task requiring its decision to create new options for highly sensitive radiometric equipment.

The proposed technical solutions provide the sensitivity, extending the functionality of radiometric equipment which is related with objects of wildlife and humans.

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